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An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling)

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ABSTRACT

BIM (building information modelling) has developed into a powerful solution that can improve many aspects of construction industry. Current research regarding the impact of orientation on a building's energy needs seldom tap into the potential of BIM. This study investigates the impact of orientation on energy consumption in small-scale construction, and assesses how BIM can be used to facilitate this process. The methods adopted are three-fold. Firstly, a real-life building is modelled using Revit, one of the leading BIM tools. Secondly, through green building Extensible Markup Language, the model is exported to Green Building Studio, one of the leading energy simulation software. Thirdly, in the Green Building Studio, different building orientations are adopted and their impacts of the whole building energy are investigated. Based on the analysis of the energy consumption corresponding to the different orientations, it emerged that a well-orientated building can save a considerable amount of energy throughout its life cycle. Specifically, a total electricity use difference of 17 056 kWh and a total gas use difference of 27 988 MJ leading to a combined energy cost savings of £878 throughout a 30 year period between the best (+180°) and worst (+45°) orientations of the building was achieved.

1. Background

According to the recent the IPCC (Intergovernmental Panel on Climate Change) AR5 (Fifth Assessment Report), globally buildings were responsible for about 32% of energy consumption and emission of 19% of energy-related greenhouse gases in 2010. These shares impact negatively on the environment and communities through global warming. With growing threats of global warming, it is not a surprise that the construction industry is now beginning to address the need for energy efficient buildings [17].

There are several factors that can influence the energy needs of a building, many of which can be managed to improve building energy efficiency. According to the International Energy Agency [30]; the energy performance of the building envelope and its components (external walls, roofs, windows etc.) can be critical in determining how much energy is required internally. Studies have suggested that lower energy consumption can be due to improved insulation and more efficient building elements [18,59]. Occupants' behaviour is suggested to impact the level of energy required for space heating in dwellings [3,37]. For example, the use of heating systems, space and appliances will differ significantly between occupants with dissimilar behaviour [53]. The shape and size of a building can have an impact on energy consumption [5,20,24,25]. Catalina et al. [20] suggested that in order to minimise heat loss, a compact shape (e.g. a cube) is required. The ability that a building has to use solar radiation for heating and lighting may influence energy efficiency, which is often determined by building orientation. As suggested by Wong and Fan [63]; it is vital to correctly orient a building so that it can receive a large solar contribution. The use of heating and lighting systems are two major factors that influence energy consumption in buildings [40], both of which relate to building orientation. In order to maximise solar gain (which is important during colder seasons), it is vital to correctly orient a building so that it can receive a large solar contribution [19,63]. Among the parameters that have an impact on passive solar gain, Morrissey et al. [42] identifies orientation as one of the most important. Pacheco et al. [49] claims that building orientation is one of the greatest repercussions on the energy demand of a building. Furthermore, Aksoy and Inalli [10] suggest that the

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optimisation of both building orientation and shape can lead to energy savings of 36%. Spanos et al. [56] argue that good orientation, location on site and landscaping changes may potentially reduce the energy requirements of a building by 20% through increasing the quantity of daylight entering an internal space. Fallahtafti and Mahdavinejad [25] investigated the impacts of 16 different formations of buildings against a fixed orientation. Xu et al. [64] used EnergyPlus to only analyse the energy saving performance by optimizing buildings' orientation of some representative cities in China. Al-Fahmawee [11] use mathematical techniques such as linear regression models to determine the impacts of different floor heights and building orientation on atrium daylighting levels.

Based on the review in the preceding paragraph, it is important to note that most studies have grounded evidence of impacts of orientation on building energy consumption. However, from methodological and technical points of view, many studies used techniques that are still too slow with higher chances of making errors in the process of computations. For example, Al-Fahmawee [11] is based purely on mathematical techniques that limit the chances of performing many real time changes about different options that can allow end-users to choose amongst the options. Furthermore, all the afore-mentioned studies about orientation on building energy performance have focused on limited number of orientation variations. Unfortunately, opportunities and capabilities enshrined in emerging BIM (building information modelling) are often being missed due to the lack of knowledge about the potential BIM in assessing the impact of building orientation on building energy efficiency.

Emerging BIM can allow professionals to virtually learn the impacts of orientation on building energy efficiency before a single brick of the building is laid on site. This can allow professionals and end-users to make so many alterations virtually and then making decisions about the various options. The novelty of this study lies in the integration of BIM systems and their use in virtually investigating the impacts of multiple orientations on building energy consumption.

Having examined the limitations of current studies and impacts of building orientation on energy consumption, the aim and objectives of this study will be discussed in Section 2. Section 3 will dwell on the research methods adopted to achieve the stated aim and objectives. In Section 4, an overview of BIM will be provided. Section 5 will dwell on the relationship between BIM and energy simulation software systems. In Section 6, the rationale or justification for choosing the different software used in this study will be discussed. Based on the chosen software in Section 6, a case study application implemented in the chosen software is examined in Section 7. In Section 8, the results, analysis and discussions will be presented. In Section 9, the results are validated using both another energy simulation software and real data from an existing energy bill. In Section 10, the opportunities and challenges in the building energy simulation process are discussed. The paper concludes by a way of summary in Section 11.

2. Aim and objectives

The aim of the study is to investigate the impact that building orientation has on energy use within small-scale construction using emerging BIM. The research objectives are to:

- explore BIM software and energy simulation systems for modelling building orientation for the purposes of energy analysis;
- investigate the impact of building orientation on energy consumption using appropriate BIM software systems
- investigate the opportunities and limitations involved in the analyses of the impact of building orientation on energy consumption in a BIM/energy simulation software environment.

3. Research methods

A number of research methods were chosen, each or a combination of more than one was/were tailored to meet specific research objective(s). To facilitate understanding the research framework will be presented in Fig. 1.

The first step consists of undertaking an extensive literature review about the different domain relevant to this study. Specifically, factors that affect building energy use, BIM and energy analysis software are reviewed. This led to the understanding of nexus between building energy orientation and building energy consumption. Furthermore, an extensive review of BIM and energy analysis software was conducted to establish their suitability for use in this study. Main literature sources for the review include material from vendors' websites and peer-reviewed publications [1,2,7–9,15,22,34,48,54,61]. Secondly, based on the different software identified in the previous step, their uses in modelling of building and energy simulation are investigated. The details of the simulation steps are indicated in Fig. 1. Thirdly, based on the preceding step, the simulation processes are implemented on a chosen case study building with well-known information. Choosing a building with well-known and established characteristics is important as it allows authors to easily analyse and interpret findings from iterating the different modelling of building orientations. This allowed for an in-depth analysis of the potential in modelling building orientation in a BIM environment. To ensure the computational results are accurate, a second software is used to verify the results. Fourthly, based on the case study analysis, one of the computed results is compared with data from a real energy data, in this case a bill. This some sort, serve as a validation of the whole computation.

4. Building information modelling: what is it?

Construction projects are becoming more complex and difficult to manage [12,21,62] and as technology develops, more construction professionals are familiarising themselves with BIM. This has led to a dramatic shift in attention towards the concept of BIM by the construction industry. BIM is currently the most common denomination for a new way of approaching the design, construction and maintenance of buildings [16]. It is the creation and use of coordinated, consistent, computable information about a building project - information that is parametric and that can be used for design decision-making, production of high-quality construction documents, prediction of building performance, cost estimating and construction planning [33]. BIM is a set of policies, processes and technologies integrated as a methodology to manage the essential building design and project data in a digital format throughout a building's life cycle [57]. Froese [26] argues that in the near future, BIM will be used to virtually construct an entire project through simulations before it is erected or constructed in reality. The fact that BIM can be used to model buildings and for analysis to be performed virtually before the buildings can be erected onsite is one of the most important strengths of BIM. It is this aspect/feature that has been exploited in this study. BIM software packages are highly needed for the development/design of the virtual building models. The urgent need to incorporate BIM in managing construction information has led to a plethora of BIM software packages in the market. Some leading and most common BIM software packages have been reviewed in Kurul et al. [34]; Abanda and Tah

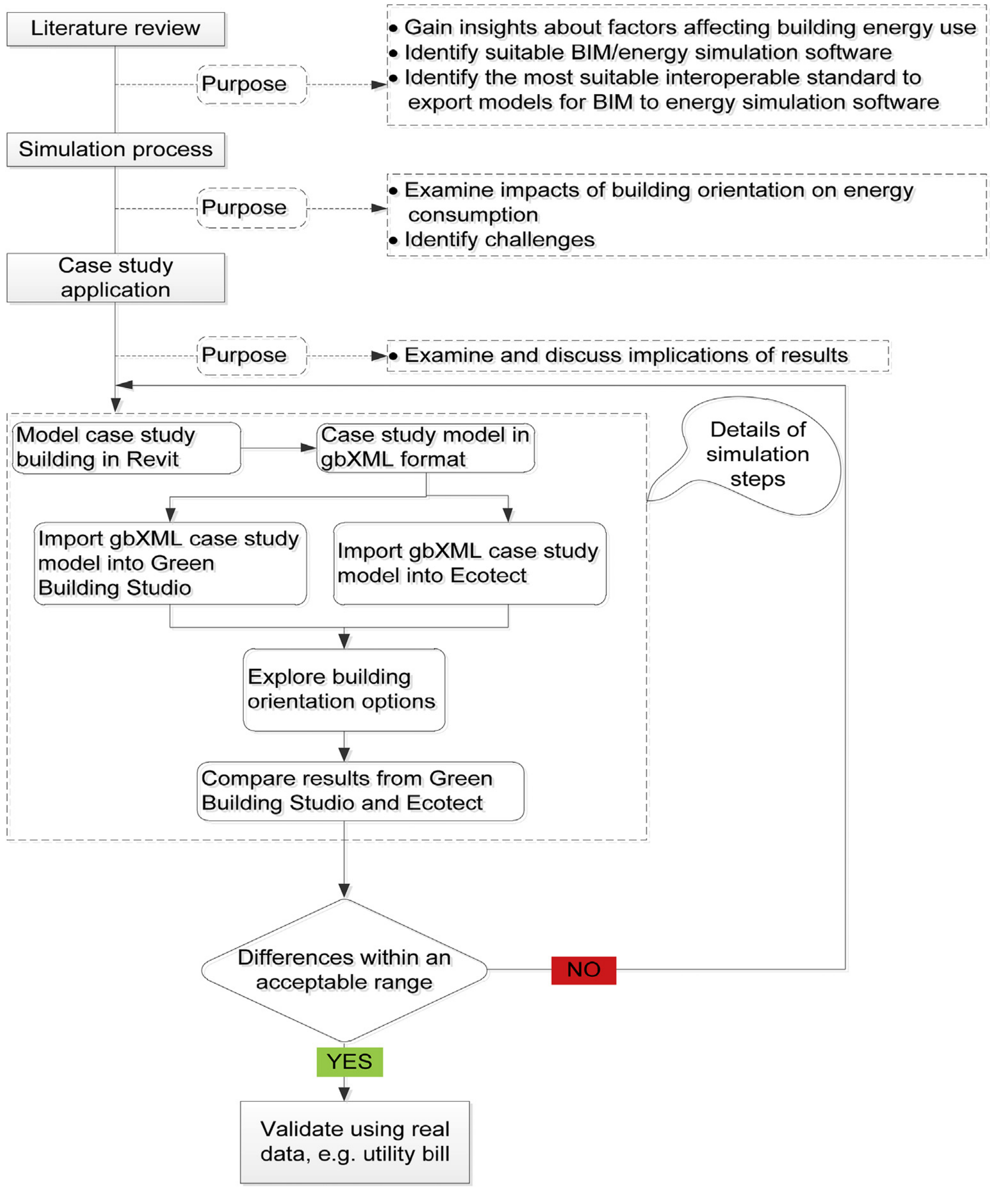

Fig. 1. Research methods framework.

[2] and NBS (National Building Specification) [44–46]. The most recent extensive review covered 122 BIM software systems in Abanda et al. [1]. This effort will not be duplicated here. However, given that the multiplicity of these BIM systems, making decisions about their uses is difficult. The criteria for the choice of the different BIM software packages will be examined in Section 6.

5. Energy simulation software systems and BIM

Many software vendors/manufacturers have created energy simulation systems that can be used to assess the efficiency of a building virtually. Similar to the multiplicity of BIM authoring tools, the market has been over flooded with many energy simulation tools making decisions about their uses is challenging. As an illustration, the US Department of Energy website provides information on 417 building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings [61]. Some of the software can be used independently from the BIM software while others can be integrated into BIM before performing energy analysis. There are some factors that need to be considered before deciding about which type of energy simulation software to use. But before examining the factors, it is important to situate the context of BIM in building energy simulation.

BIM has the capabilities to assist its user in achieving a more energy efficient building [41]. Energy analysis is often complex and expensive and as a result it is sometimes delayed until the end of the design process [41]. The integrative character embedded within BIM allows coordinated and reliable information about the building project to be used from the initial design stage. Tucker and Newton [60] state that BIM allows for multidisciplinary information to be superimposed within one model, incorporating structural, mechanical, electrical, plumbing and lighting. The consistent and interconnected information that creates a BIM model can be used to facilitate building energy analysis early in the process. The data generated from such simulations can be used to create more efficient design alternatives in a quick and cost effective way.

Azhar and Brown [13] suggests that BIM and energy modelling can be used to assess a building's orientation and positioning with respect to daylighting, thus enhancing its efficiency through solar heat gain. Niewoehner [47] furthers this by suggesting that the real time integration of the information database can yield real time analysis of energy usage, heat load/loss and daylighting.

Krygiel and Nies [33] suggest that BIM can assist the following aspects of efficient design:

- Building massing, used to analyse a building's form and optimise its envelope – Used to assess heat transfer through the building envelope in order to manage heating and cooling loads [27];
- Energy modelling, to reduce energy needs and analyse renewable energy options – BIM can be used to understand the total energy cost of a building before it is constructed, making it easier to recognise ways of building more efficiently;
- Building orientation, via selecting a good orientation – Building orientation has an impact on a building's ability to naturally heat an internal space. A BIM model can be used to understand the impact that orientation may have on energy consumption during the early stages of a project [28,41].

As earlier discussed, some energy simulation software systems are linked to BIM software while others are not. It is important to understand this relationship as it facilitates the understanding of which software or combination of software to be used for energy simulation and analysis. This will be considered in Section 6.

6. Rationale for the choices of the different software for building orientation simulation

Four main criteria were used to select the software used in this study. Firstly, a study by Kurul et al. [34] reveal Revit is one of the most popular BIM authoring tools currently being used in the construction industry. This was corroborated by surveys conducted by the NBS (National Building Specification), that has consistently placed Revit top two by usage and preference in the UK since 2012 [44–46]. Once a building has been modelled, there is need to choose a specialist energy simulation software. To this end, Green Building Studio for energy simulation was chosen. This was chosen because of the fact that so many orientations can be chosen and impact generated in real-time, without the need to revert to the original geometric model. Thirdly, there is need for the BIM software to communicate with the energy simulation software. The aspect of communication is often treated under the concept of interoperability. Many authors have defined interoperability differently, but the various definitions usually have a common meaning, although with subtle differences. The subtle differences are out of the scope of this study. According to Rezaei et al. [51] and Bahar et al. [14]; interoperability refers to the possibility of communication, data exchange and use, between two (or more) different software. Kensek [32] defines interoperability as “the ability to effectively transfer project data to different domains and platforms”. It identifies the need to pass data between applications without replication and allow multiple applications to be utilized simultaneously at different phases of the project [23].

To support building data transaction between BIM applications and building energy analysis tools, significant success has been reported with the development of XML (extensible markup language) – based schemas. One of the most common data format for such information exchange or interoperability is the gbXML (Green Building XML) format [55]. Laguela et al. [35] enforced the claim stating that gbXML is the defacto selected schema for the writing of BIM models, due to its capacity to incorporate thermal descriptive data. The gbXML schema can be conceived as a database where descriptive information is linked with geometry [35]. The use of gbXML suggests that by importing geometric models from BIM software into energy simulation tools without the need to recreate the building geometry within the simulation interface, significant time savings can be realised [29]. The last reason for choosing Revit and Green Building Studio was the fact that both can seamlessly communicate through gbXML. A building geometry can be exported from Revit to Green Building Studio for energy analysis. Also, in order to verify the results from Green Building Studio, another energy simulation software Ecotect was used to compute the annual energy consumption of the case study building. The results from both energy simulation software systems were the same with very insignificant differences. Ecotect offers a wide range of simulation and building energy analysis functionality that can improve performance of existing buildings and new building designs. It can be used to compute heating and cooling loads for building models and analyse effects of occupancy, internal gains, infiltration and equipment. Furthermore, Ecotect can read gbXML file formats. After the verification of the results, it was validated by comparing with the real energy bill of the case study.

7. A case study application

7.1. Case study and scenario descriptions

The case study building is small-scale domestic construction currently being inhabited by a family. It is a 3-storey house located in Hertfordshire, CM23 5NW, UK. The ground floor consists of two living spaces, a kitchen, a dining room and a WC. The first floor comprises three bedrooms, a bathroom and a WC and the roof conversion comprises of two additional bedrooms. The choice of the case study is based on the fact that one of the co-authors of this paper has connections with the building owner and can readily gain access to the building to reconstitute the drawings and also obtain energy bills for validation of results.

A series of tests was conducted to measure the impact that building orientation has on the energy use. In this instance, the term ‘test’ refers to the use of Green Building Studio to manipulate a building model and gather details regarding its energy use. Energy analysis of the initial building model (front of the building facing directly north) will provide data for test 1. Test 2 will assess the case energy use at a $+45^\circ$ orientation, test 3 at $+90^\circ$, test 4 at $+135^\circ$, test 5 at $+180^\circ$, test 6 at -135°, test 7 at -90°, test 8 at -45°, test 9 at 150° and test 10 at 165°. An 11th test was undertaken to represent the actual building's orientation, which is at 157.5°.

7.2. Model development

Given the lack of drawings of the case study building, the authors surveyed the site and reconstituted the drawings manually using measurement equipment. The reconstituted drawings were then modelled using Revit (see Fig. 2). To conduct the energy simulation, the building model was exported from Revit using gbXML, with the process as shown in Fig. 3.

When the model is fully converted, it can be saved as a gbXML file, and then Green Building Studio can be used to read the file.

7.3. Energy simulation in Green Building Studio

Figure 4 shows the type of details that Green Building Studio requires for, when creating a new project. Green Building Studio automatically selects the project's nearest weather station in order to obtain relevant information that will be used during the simulation.

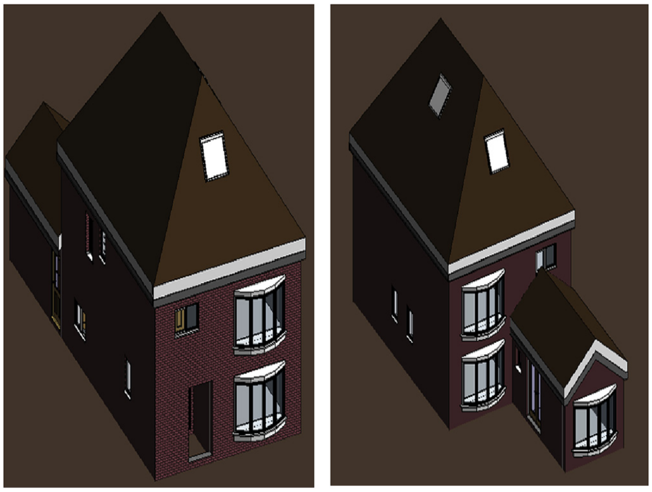

Fig. 2. Case study building.

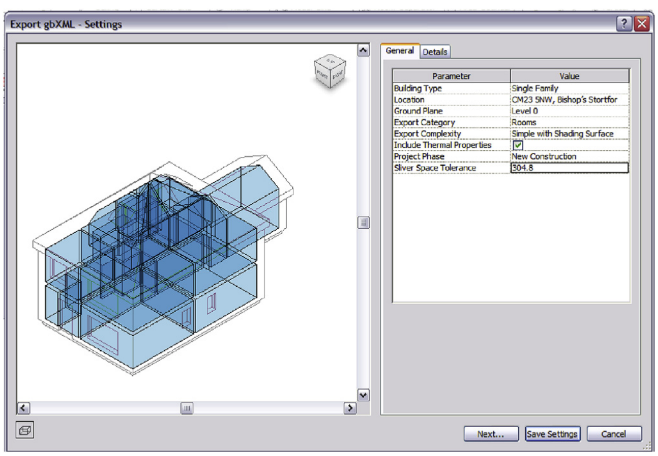

Fig. 3. Conversion process to gbXML.

Furthermore, the current utility rates that are representative of the location were inputted. Average current UK prices were used in this instance and were obtained from UKPower.co.uk. An electricity cost of £0.105/kWh and a gas price of £0.54/Therm were used (See Fig. 5).

Green Building Studio automatically calculates various energy use information including total annual energy use as shown in Fig. 6.

In order to compare and observe the impact that building orientation has on energy use, a number of additional 'runs', or design alternatives were added to the project. This is the major strength of Green Building Studio. To do this, the design alternatives tab is selected, and changes to the base run are made. Fig. 7 shows a design alternative with a rotation of $+90^\circ$ being created.

The data created by the initial base run (no changes made in Green Building Studio) is used for test 1, test 2 incorporates a change of 45° and test 3, a change of 90° etc. Similarly, changes for other scenarios are effected and typical results output for each scenario are presented in Fig. 8.

As the building's orientation changes, a different elevation will be susceptible to the sun's radiation. A building's ability to naturally heat an internal space depends on its exterior components and the way in which they interact with the sun. In each test instance, a different facade of the building will be facing southerly direction. The sun rises in the East and sets in the West, therefore a building located in the UK (Northern hemisphere) should face South in order to take maximum advantages of the sun's energy to naturally heat the building in colder months. When creating the model using Autodesk Revit, the building was produced so the front (where the entrance is located) faces directly the North. The model tested in its natural position without alterations in Green Building Studio is called the base run and is used for test 1. The model is then rotated to 45° increments clockwise to create an additional 10 test scenarios. An 11th test is then conducted to represent the orientation of the actual building in order to use it to validate computation results.

8. Results, analysis and discussions

The case study results can now be presented, analysed and discussed to understand the relationship between building orientation and energy consumption of a small-scale domestic building. The assumptions made in Green Building Studio are that the total life cycle of the building will be 30 years with a discount factor of 6.1% for costs. Energy loss through electronic transmission is not included. Green Building Studio refers to gas as "fuel". The building's estimated energy used at each orientation, the building position, the facade that would be facing Southerly direction in each instance/test will be discussed in the ensuing sections.

8.1. Scenario analysis

Test 1: Base run: In this case, the front of the building is North facing, the rooms at the front of the house include a secondary living space (used only during the winter), a spare bedroom, a study

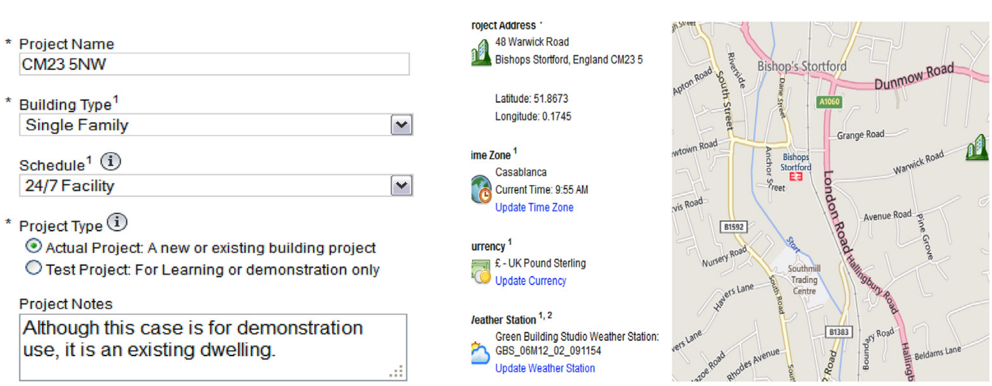

Fig. 4. Project information in Green Building Studio.

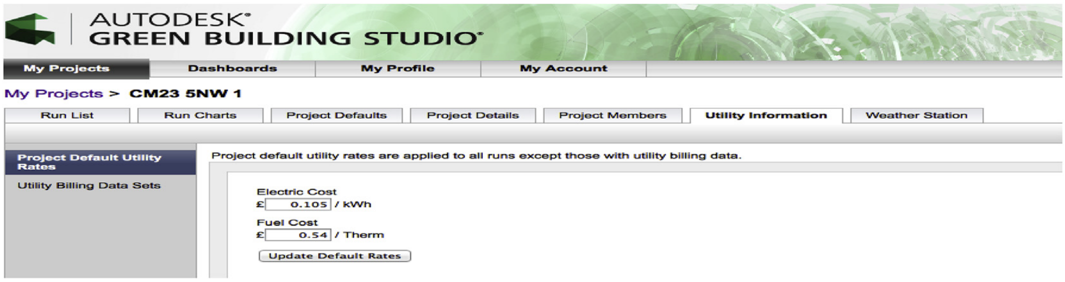

Fig. 5. Updating utility cost.

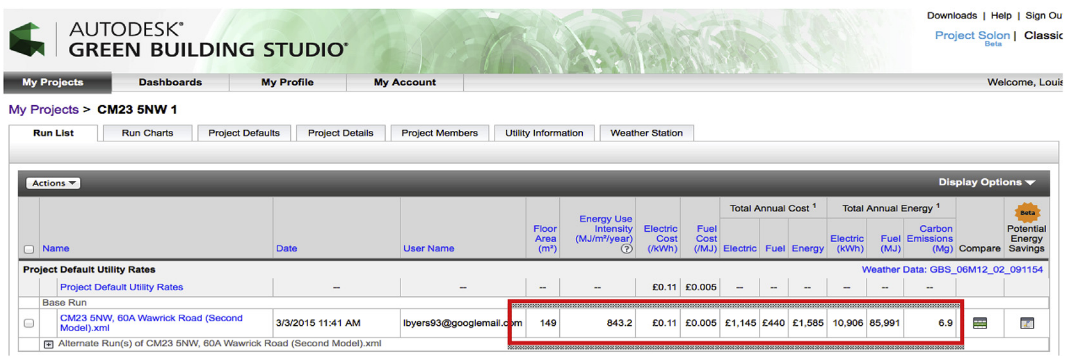

Fig. 6. Computed results of energy use.

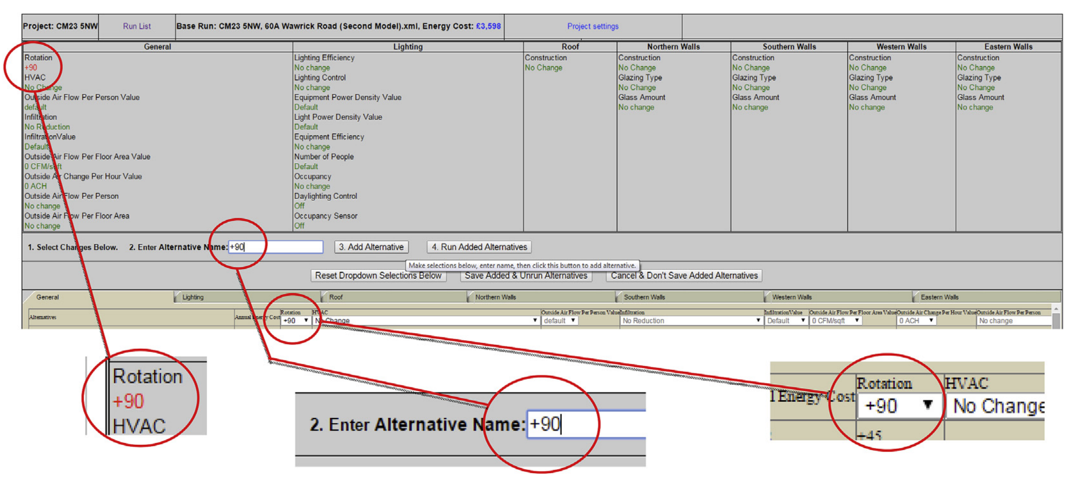

Fig. 7. Creating design alternatives.

and a loft converted bedroom. The total annual electricity and fuel energy consumed are 10 906 kWh and 85 991 MJ both costing £1585 in total.

Test 2: **+45°**: To conduct the second test, Green Building Studio was used to create a design alternative with an orientation of +45° from the base run. The angle of the building changes the percentage of window area across the front of the building that would be susceptible to the sun shining from the South. The total annual electricity and fuel energy consumed are 11 043 kWh and 87 816 MJ both costing £1609 in total.

Test 3: **+90°**: At a 90° the southerly facing facade incorporates just 3 windows, however, the bay windows located on the front and back of the building may influence a low level of internal solar gain. The total annual electricity and fuel energy consumed are 10 929 kWh and 89 039 MJ both costing £1603 in total.

Test 4: **+135°**: This is the face of the building with the highest volume of window units and is orientated towards the South. The total annual electricity and fuel energy consumed are 10 654 kWh and 87 794 MJ both costing £1568 in total.

Test 5: **+180°**: With three sets of bay windows, a double window and a velux window, all facing directly South. The total annual electricity and fuel energy consumed are 10 475 kWh and 86 883 MJ both costing £1545 in total. Also, the primary living spaces (the main living room and dining room), are facing directly South in this iteration.

Test 6: **−135°**: Test 6 suggests that prices begin to rise as the building is re-oriented. The total annual electricity and fuel energy consumed are 10 584 kWh and 86 584 MJ both costing £1556 in total. The building still benefits from a large array of window units facing South.

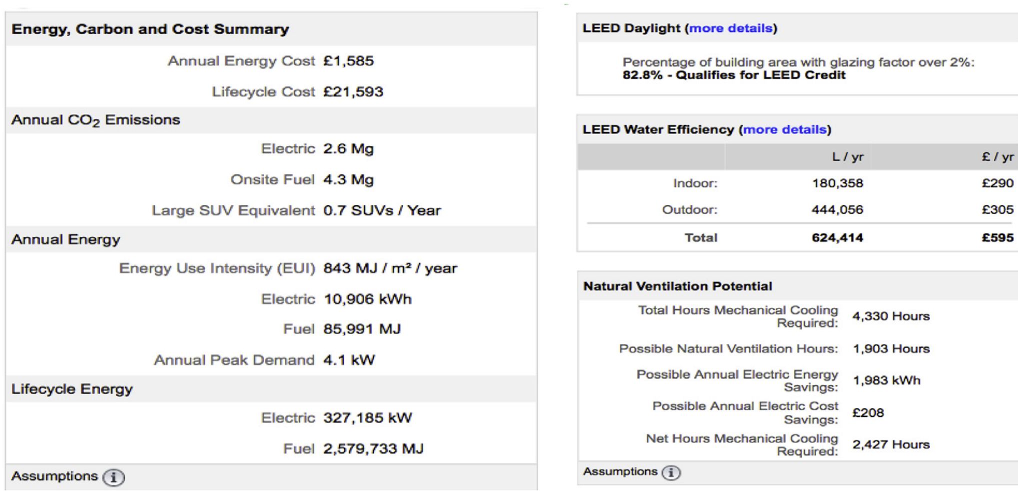

Fig. 8. Typical results output of a scenario simulation.

Test 7: −90°: At building orientation of −90°, the total annual electricity and fuel energy consumed are 10 690 kWh and 87 032 MJ both costing £1568 in total.

Test 8: −45°: At an orientation of −45° from base run, the building has several windows facing a southerly direction; however none of them are directly South facing. The total annual electricity and fuel energy consumed are 10 822 kWh and 86 498 MJ both costing £1579 in total.

Test 9:+150°: At building orientation of +150°, the total annual electricity and fuel energy consumed are 10 566 kWh and 87 418 MJ both costing £1557 in total.

Test 10: +165°: At building orientation of +165°, the total annual electricity and fuel energy consumed are 10 506 kWh and 87 095 MJ both costing £1549 in total.

Test 11: +157.5°: In order to compare the energy use figures generated by Green Building Studio with the actual energy bills stored by the homeowner to prove validity, an 11th test has been conducted to represent the buildings actual orientation. As shown in Fig. 9, the back of the building is angled so that it faces between the South and South-East (+157.5°).

The average between the +150° and +165° orientations (Tests 9 and 10) has been used to determine the +157.5° angle, which represents the 11th test. By taking the averages, the total annual electricity and fuel energy consumed for test 11 are 10 536 kWh and 87 257 MJ both costing £1553 in total.

In addition to the preceding analyses, life cycle energy and life cycle cost have been computed and summarised in Table 1.

Given that cost depends on energy consumed, only the annual and life cycle cost of energy will be examined. The annual energy cost is presented in Fig. 10 and ranges from a low of £1545 to a high of £1609. Furthermore, the total life cycle cost ranges from £21 038 up to £21 916, a total difference of £878 (£21 474 (see Fig. 11)).

8.2. The impact building orientation on energy use

Through conducting a case study, the researcher has been able to generate quantitative data which can be used to address the research aim and objectives. The case study focuses on the manipulation of a 3D BIM model using Green Building Studio to test the building's estimated energy use at a series of orientations. The way in which a building is positioned relative to the sun's path can impact its ability to naturally heat the building envelope through solar gain. After conducting a thorough examination, the relationship between the two variables is clear, and the level in which one impacts the other is evident.

Although the range of data may not seem significant from year-to-year, the impact that orientation has on a building's life cycle energy cost is substantial. The lowest annual energy cost figure of £1545 at +180° from base level compared to the upper range of £1609 at +45° from base level is an increase of £64. The difference in cost over a 30-year period between the best orientation at £21 038 and the worst orientation at £21 916 is £878.

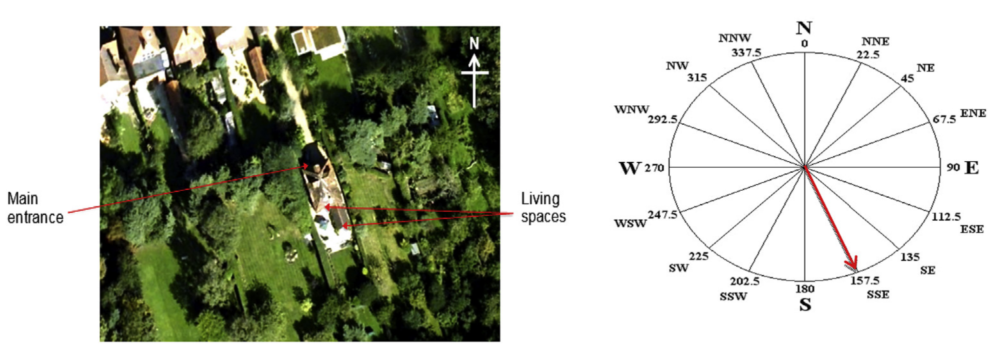

Fig. 9. Actual building orientation SSE (South-South East).

Table 1
Summary of energy used and cost for the case study building.

	Annual		Life cycle		Annual energy cost (£)	Life cycle cost (£)
	Electric (kWh)	Fuel (MJ)	Electric (kWh)	Fuel (MJ)		
Test 1	10 906	85 991	327 185	2 579 733	1585	21 593
Test 2	11 043	87 816	331 303	2 634 468	1609	21 916
Test 3	10 929	89 039	327 861	2 671 182	1603	21 837
Test 4	10 654	87 794	319 626	2 633 813	1568	21 358
Test 5	10 475	86 883	314 247	2 606 480	1545	21 038
Test 6	10 584	86 584	317 507	2 605 612	1556	21 191
Test 7	10 690	87 032	320 701	2 610 949	1568	21 356
Test 8	10 822	86 498	324 666	2 594 936	1579	21 508
Test 9	10 566	87 418	316 985	2 622 528	1557	21 206
Test 10	10 506	87 095	315 184	2 612 847	1549	21 097
Test 11	10 536	87 257	316 085	2 617 688	1553	21 152

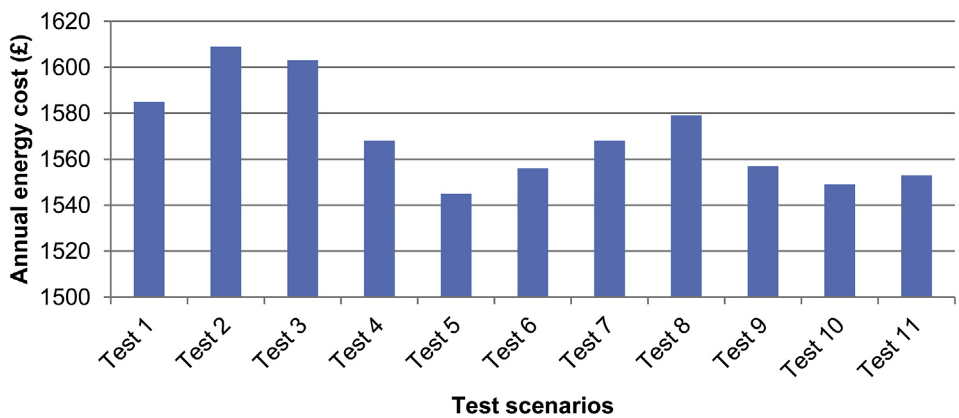

Fig. 10. Annual energy cost for the different scenarios.

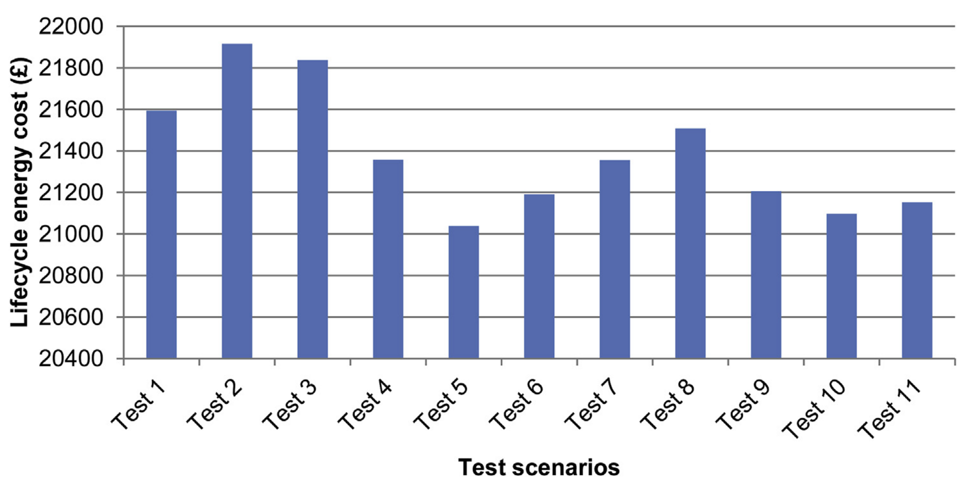

Fig. 11. Lifecycle energy cost for the different scenarios.

The most cost effective orientation for the case under investigation is $+180°$ from base level. That orientation contains an external facade that would be facing a southerly direction. The facade incorporates a large array of bay windows. Due to the ability a window has to absorb solar radiation, an exterior building frontage with a large number of window units will usually facilitate a higher level of solar heat gain internally, as suggested by Morrissey et al. [42]. As a rule of thumb, buildings are often positioned so that living areas are facing south so that the rooms that are used most often, benefit from the sun's heat [38]. As shown in Fig. 9, the building is positioned well so that the primary living areas (living room and dining room) are facing a southerly direction. The west facade is slightly facing south, however the eastern elevation contains a larger array of window units, meaning that the actual building could be orientated differently in order to reduce its energy needs.

9. Validation of computation results

In this section, two validation techniques adopted will be discussed. The first is the verification of computational results using

Ecotect, a similar energy simulation software to Green Building Studio. After the verification, the computational results of the annual energy from Green Building Studio are compared with the real utility bill of the case study building.

9.1. Validation of computational results: Green Building Studio versus Ecotect

For BIM and energy simulation systems to be trusted, the results generated from them should be accurate. In this first instance, the annual energy consumption for the different test orientations was computed using Ecotect (see Table 2) to verify the computational accuracies from Green Building Studio.

Based on Table 2, the percentage difference between the totals is 1.02% [(388 184.2−384 213.1)/388 184.2*100], which is very insignificant. Disparity in the computational results from energy simulation software is not uncommon. The 1.02% is quite small compared to results from other studies. Reeves et al. [50] determined the annual cooling energy for the same case studies to be different using three different energy simulation software, i.e. IES-VE (Ecotect, Environmental Solutions-Virtual Environment), Green Building Studio. For Ecotect, IES-VE and Green Building Studio, the results were 3.86%, −45.1% and −72.83% with regards to the annual cooling energy bill respectively. More recently, in Stundon et al. [58]; the energy use estimated by IES-VE yielded ±8% while that of Green Building Studio yielded ±5% with respect to the utility bills of the same case studies. One of the reasons why there is variability in the accuracy of results can be related to occupancy's schedules which depends on human behaviour. As argued in Ryan and Sanquist [52]; schedules are common sources of errors in energy simulation software because the behaviour of occupants is highly variable and nearly impossible to model accurately. Given that 1.02% is small compared to accuracies from other studies (e.g. Refs. [50] and [58]) and the challenge in overcoming unpredictable human behaviour in dwellings, the computational results obtained from Green Building Studio in this study can reasonably be considered accurate.

9.2. Comparison of computational results with real energy bills

As earlier discussed, the current orientation of the building (test 11) was approximated, its energy consumed and corresponding cost were then computed. The aim of this was to compare with cost of the bills obtained from the real building. Real energy bill is empirical, often called “true” data, considered a very powerful validation tool since it can be used in comparing with auditing data [31]. Furthermore, Ryan and Sanquist [52] proposed that simulation results obtained by building energy simulation software should be validated by comparing with measured data for an actual building. Based on the aforementioned arguments, the energy bill of the case study building was compared to the simulated results obtained from Green Building Studio. Fig. 12 shows the household energy bills at XX Warwick Road, CM23 5NW. XX is a fictitious number as we do not want to reveal the address of the home for data protection purposes. Names of house owners have been cropped from the bills for the same reason.

The total annual energy cost that the homeowners paid in 2014 was £1941.23. The results generated by Green Building Studio presented in test 11 (actual building orientation) suggest a total energy use cost of £1553. The real value of £1941.23 is about 25% greater than the computed value from Green Building Studio. It is important to note that the bills in Fig. 12 are for the year 2014. However, the current UK unit rates (i.e., the year 2015) were used to conduct the Green Building Studio tests, which differ from the rates in 2014. The UKPower.co.uk does not provide the possibility to obtain rates for the previous years. Hence the rates used in Green Building Studio were those of 2015. As reported by Murray [43] in October 2015, wholesale electricity was 20% lower than it was at the start of 2014, and wholesale gas was 37% less. This is clearly within the 25% margin and confirms the accuracy of computation using Green Building Studio. This suggests that if the rates of 2014 instead 2015 were used in the Green Building Studio, the total energy cost will be much closer to the value obtained from the (i.e. £1941.23). This can be determined by including the wholesale electricity of 20% and the wholesale gas of 37% to the energy cost £1553. We will consider three values here, the minimum (20%), average [28.5% = (20% + 37%)/2] and maximum (37%).

Considering the average value of 20%, the margin of error between the simulated value in Green Building Studio and the energy bill is = [£1941.23-(0.2*£1553 + £1553)]*100/£1941.23 = 4%.

Considering the maximum value of 28.5%, the margin of error between the simulated value in Green Building Studio and the energy bill is = [£1941.23-(0.285*£1553 + £1553)]*100/£1941.23 = −2.8%.

Considering the minimum value of 37%, the margin of error between the simulated value in Green Building Studio and the energy bill is = [£1941.23-(0.37*£1553 + £1553)]*100/£1941.23 = −9.6%.

According to Maamari et al. [39] and Reeves et al. [50]; the accepted percentage error between computer simulation results and empirical or measured data should be in the range ±15% for the software to be considered accurate. The three computed percentage errors are 4%, −2.8% and −9.6%, which are clearly within accepted range.

That notwithstanding it is important to highlight possible sources of errors which can influence the computational results:

- The orientation of a building can be difficult to accurately predict, therefore the orientation used to conduct the Green Building Studio test may not precisely represent the buildings actual orientation;
- A number of assumptions made in the computation using Green Building Studio tests. The actual building elements may represent different U-values and Solar Heat Gain Co-efficient from the assumed values used in Green Building Studio;
- Green Building Studio estimates the amount of unregulated energy use depending on a fixed level of occupancy. The actual occupancy level may differ from month to month in each year.

Table 2
Computational results: Green Building Studio versus Ecotect.

Annual energy consumption (kWh)		
	Green Building Studio	Ecotect
Test 1: 0°	10 906 kWh + 85 991 MJ = 34 792.4	35 900
Test 2: +45°:	11 043 kWh + 87 816 MJ = 35 436.3	35 891.6
Test 3: +90°:	10 929 kWh + 89 039 MJ = 35 662.1	35 809.6
Test 4: +135°:	10 654 kWh + 87 794 MJ = 35 041.2	35 728
Test 5: +180°:	10 475 kWh + 86 883 MJ = 34 609.2	34 409
Test 6: −135°:	10 584 kWh+86 584 MJ = 34 635.1	34 948
Test 7: −90°:	10 690 kWh + 87 032 MJ = 34 865.6	34 910
Test 8: −45°:	10 822 kWh + 86 498 MJ = 34 849.2	34 802
Test 9: +150°:	10 566 kWh + 87 418 MJ = 34 848.8	34 956
Test 10: +165°:	10 506 kWh + 87 095 MJ = 34 699.1	34 920
Test 11: +157.5°:	10 536 kWh + 87 257 MJ = 34 774.1	34 910
	384 213.1	388 184.2

Fig. 12. Real bill (gas bill to left and electricity bill to the right) of the case study building.

10. Opportunities/limitations in building energy simulation in BIM environments

In this paper, the possibility and capability of BIM to virtually model and assess buildings' energy consumption against parameters such as their orientations offers the opportunities to explore alternatives before undertaking the building development. This is a great opportunity to avoid mistakes that might arise should the building be assessed using manual or traditional techniques. Furthermore, when such mistakes occur, it is difficult to correct when the building is already in operation or use. However, despite this capability of BIM in making decisions virtually, there are still some limitations that if addressed, its potential can even reach unimaginable levels.

Firstly, the weather station chosen is often an approximate depending on the location of the building. In the case of this study, the building is located in Bishop's Stortford, London, Cambridge and Standsted Airport weather stations are the nearest to the building location. However, Standsted which is the closest amongst the three is not included in most weather database systems, e.g. the weather database embedded in Ecotect. Thus, the Cambridge weather station was chosen for this study.

Secondly, as earlier alluded to there is no real time connection between authoring BIM and energy simulation software. This means that once the building is modelled in authoring BIM software, it must be complete and accurate before being exported via gbXML to an energy simulation software. If after export, errors are discovered with the gbXML version, then the model will to be fixed and re-exported again to the energy simulation software. There is no real time connection between the energy simulation software and the BIM authoring software.

Lastly, errors due to occupants' presence in a building are difficult to completely avoid. As argued in Ryan and Sanquist [52]; the behaviour of occupants is highly variable and nearly impossible to model accurately. This presents a huge challenge to deal with in most energy simulation software systems.

11. Conclusions

Many factors influence the energy needs of a building including building envelope, building components, occupant behaviour, building orientation, building size and shape. The ability that a building has to naturally heat and light its internal spaces can significantly reduce the need for artificial systems. The way in which a building is orientated on site and therefore interacts with the sun, largely determines internal solar gain. Reduced needs for heating and lighting units will reduce energy use and improve efficiency. While this might have been corroborated by existing studies [6,36], quantitative evidence has largely depended on manual and often error-prone computation. The potential of emerging BIM have seldom been considered in energy simulation studies. Thus the benefits of assessing energy needs of a building virtually before erecting the building on site are not being reaped. In this study Revit and Green Building Studio were both used to perform energy analysis based on changes in building orientation. This was based on a case study building located in the UK. The case study suggested that a well-orientated domestic building could save a possible £878 worth of energy throughout its lifetime. The worst degree orientation for the studied case study is at 45° (Test 2) while the best is at 180° (Test 5). The latter is in conformity with most buildings in the UK, where the best orientation is South facing. The current orientation of the dwelling is 22.5° (=180°−157.5°) from the South.

The investigation has been successful in proving that building orientation impacts energy use and that the impact can be substantial. It has also provided the steps involved and how Revit and Green Building can be connected albeit via gbXML to perform energy analysis.

However, it is important to note that the virtual manipulation takes place independently within Revit and Green Building Studio. The implication is that a building model must be developed up to the required and agreed standard in Revit before being exported to Green Building Studio. While in Green Building Studio, virtual manipulations can be performed to study impacts of building orientation. Also, the finding from this study was validated with a real bill, which proved the Green building Studio computational values were within range. However, given that case study approach cannot be generalised, part of our future study will be to use so many buildings and also perform similar analysis in different energy simulation software to compare results.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2015.12.135.

References

[1] Abanda FH, Vidalakis C, Oti AH, Tah JHM. A critical analysis of building information modelling systems used in construction projects. Adv Eng Softw 2015;90:183–201.

[2] Abanda H, Tah JHM. Free and open source building information modelling for developing countries. In: ICT for Africa 2014 Conference, October 1-4, 2014 Yaoundé, Cameroon; 2014.

[3] Abanda FH, Cabeza L. Investigating occupants' behaviour using emerging building information modelling. In: ICSC15-The CSCE International Construction Specialty Conference, Vancouver, June 7–10, 2015; 2015.

[5] AlAnzi A, Seo D, Krarti M. Impact of building shape on thermal performance of office building in Kuwait. Energy Convers Manag 2009;50(3):822–8.

[6] Al-Homoud MS. Performance characteristics and practical applications of common building thermal insulation materials. Build Environ 2005;40(3): 353–66.

[7] Attia S. State-of-the-art of existing early design simulation tools for net zero energy buildings: a comparison of ten tools. Architecture et climat at Université catholique de Louvain; 2011.

[8] Attia S, Beltrán L, Herde AD, Hensen J. Architect friendly: a comparison of ten different building performance simulation tools. In: Building Simulation: Eleventh International IBPSA Conference; 2009. p. 204–11.

[9] Attia S, Gratia E, De Herde A, Hensen JLM. Simulation-based decision support tool for early stages of zero-energy building design. Energy Build 2012;49: 2–15.

[10] Aksoy U, Inalli M. Impacts of some building passive design parameters on heating demand for a cold region. Build Environ 2006;12(41):1742–54.

[11] Al-Fahmawee E. Analyzing the impact of floor height and building orientation on atria daylighting levels. Jordan J Appl Sci "Natural Sci Series" 2013;11(1): 75–88.

[12] Alshawi B, Ingirige B. Web-enabled project management an emerging paradigm in construction. Automat Constr 2003;12(4):349–64.

[13] Azhar S, Brown J. BIM for sustainable analysis. Int J Constr Educ Res 2011;5(1): 276–92.

[14] Bahar YN, Pere C, Landrieu J, Nicolle C. A thermal simulation tool for building and its interoperability through the building information modeling (BIM) platform. J Build 2013;3(2):380–98.

[15] Bambardekar S, Poerschke U. The architect as performer of energy simulation in the performance based design. In: Building Simulation: 11th International IBPSA Conference; 2009. p. 1306–13.

[16] Bryde D, Broquetas M, Volm JM. The project management of building information modelling. Int J Proj Manag 2013;31:971–80.

[17] Bynum P, Issa R, Olbina S. Building information modelling in support of sustainable design and construction. J Constr Eng Manag 2013;139(1):24–34.

[18] Caldera M, Corgnati SP, Filippi M. Energy demand for space heating through a statistical approach: application to residential buildings. Energy Build 2008;40:1972–83.

[19] Carbonari A, Rossi G, Romagnoni P. Optimal orientation and automatic control of external shading devices in office buildings. Environ Manag Health 2002;13(4):392–404.

[20] Catalina T, Virgone J, Lordache V. Study on the impact of building form on the energy consumption. In: Proceedings of Building Simulation 2011: 12th Conference of International Performance Simulation Association, Sydney, 14–16 November. Romania: Technical University of Civil Engineering Bucharest; 2011.

[21] Chan APC, Scott D, Chan APL. Factors affecting the success of a construction project. J Constr Eng Manag 2004;130(1):153–5.

[22] Crawley DB, Hand JW, Kummert M, Griffith BT. Contrasting the capabilities of building energy performance simulation programs. Build Environ 2008;43: 661–73.

[23] Eastman C, Teicholz P, Sacks R, Liston K. BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors. Hoboken, New Jersey: John Wiley & Sons, Inc.; 2008.

[24] Faizi F, Noorani M, Ghaedi A, Mahdavinejad M. Design an optimum pattern of orientation in residential complexes by analyzing the level of energy consumption (case study: Maskan Mehr Complexes, Tehran, Iran). Procedia Eng 2011;21:1179–87.

[25] Fallahtafti R, Mahdavinejad M. Optimisation of building shape and orientation for better energy efficient architecture. Int J Energy Sect Manag 2015;9(4): 593–618.

[26] Froese M. The impact of emerging information technology on project management for construction. Automat Constr 2010;19(5):531–8.

[27] Ghedamsi R, Settou N, Saifi N, Dokkar B. Contribution on building design with low consumption of energy incorporated PCMs. Energy Procedia 2014;50: 322–32.

[28] Garcia EG, Zhu Z. Interoperability from building design to building energy modeling. J Build Eng 2015;1:33–41.

[29] Ham Y, Golparvar-Fard M. Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. Automat Constr 2015;49(part B):214–22.

[30] International Energy Agency. Technology roadmap: energy efficient building envelopes. 2013 [online] Available from: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf [accessed 20.02.15].

[31] Jensen SO. Validation of building energy simulation programs: a methodology. Energy Build 1995;22:133–44.

[32] Kensek KM. Building information modeling. Routledge; 2014.

[33] Krygiel E, Nies B. Green BIM: successful sustainable design with building information modelling. Canada: Wiley; 2008.

[34] Kurul E, Abanda FH, Tah JHM, Cheung F. Rethinking the build process for BIM adoption. In: CIB World Building Congress Construction and Society, 5–9 May 2013, Australia; 2013.

[35] Laguela S, Diaz-Vilarino L, Armesto J, Arias P. Non-destructive approach for the generation and thermal characterization of an as-built BIM. Constr Build Mater 2014;51:55–61.

[36] Lam JC, Wan KKW, Tsang CL, Yang L. Building energy efficiency in different climates. Energy Convers Manag 2008;49(8):2354–66.

[37] Leth-Petersen S, Togeby M. Demand for space heating in apartment blocks: measuring effect of policy measures aiming at reducing energy consumption. Energy Econ 2001;23:387–403.

[38] Littlefair P. Daylight, sunlight and solar gain in the urban environment. Sol energy 2001;70(3):177–85.

[39] Maamari F, Andersen M, de Boer J, Carroll W, Dumortier D, Greenup P. Experimental validation of simulation methods for bi-directional transmission properties at the daylighting performance level. Energy Build 2006;38: 878–89.

[40] Mardookhy M, Sawhney R, Ji S, Zhu X, Zhou W. A study of energy efficiency in residential buildings in Knoxville, Tennessee. J Clean Prod 2014;85:241–9.

[41] Moakher P, Pimplikar S. Building information modelling and sustainability-using design technology in energy efficiency modelling. J Mech Civ Eng 2012;1(20):10–21.

[42] Morrissey J, Moore T, Horne RE. Affordable passive solar design in a temperate climate: an experiment in residential building orientation. Renew Energy 2011;36(2):568–77.

[43] Murray A. Falling energy prices? this is the best way to take advantage. 2015 [Online], http://www.telegraph.co.uk/finance/personalfinance/energy-bills/10970226/Bills-soar-by-up-to-193-how-to-beat-the-rise.html [December 2015].

[44] NBS. National BIM report 2012. 2012. Retrieved December 24, 2014 Available from: http://www.thenbs.com/pdfs/NBS-NationalBIMReport12.pdf.

[45] NBS. NBS national BIM survey. 2013. Available from: http://www.thenbs.com/pdfs/NBS-NationlBIMReport2013-single.pdf [accessed 15.03.12].

[46] NBS. NBS national BIM report 2015. 2015. Retrieved, http://www.thenbs.com/pdfs/NBS-National-BIM-Report-2015.pdf.

[47] Niewoehner D. BIM and life-cycle analysis help determine value of green strategies. Lab Des 2010;15(2):3–7.

[48] Nguyen A-T, Reiter S, Rigo P. A review on simulation-based optimization methods applied to building performance analysis. Appl Energy 2014;113: 1043–58.

[49] Pacheco R, Ordonez J, Martinez G. Energy efficient design of building: a review. Renew Sustain Energy Rev 2012;16(6):3559–73.

[50] Reeves T, Olbina S, Issa R. Validation of building energy modeling tools: Ecotect™, Green Building Studio™ and IES™. In: Laroque C, Himmelspach J, Pasupathy R, Rose O, Uhrmacher AM, editors. Proceedings of the 2012 Winter Simulation Conference. Berlin: Germany; 2012.

[51] Rezaei R, Chiew TK, Lee SP, Aliee ZS. Interoperability evaluation models: a systematic review. Comput Ind 2014;65(1):1–23.

[52] Ryan EM, Sanquist TF. Validation of building energy modeling tools under idealized and realistic conditions. Energy Build 2012;47:375–82.

[53] Santin GO. Occupant behaviour in energy efficient dwellings: evidence of a rebound effect. J Hous Built Environ 2012;28:311–27.

[54] Sharma R, Prouhit DJM. Energy analysis for building designers through computer software. Int J Innov Sci Eng Technol 2014;1(6).

[55] Sokolov I, Crosby J. Utilizing gbXML with AECOsim building designer and speedikon: building performance analysis using Bentley products. 2011 [online] Available from: http://ftp2.bentley.com/dist/collateral/docs/white_papers/WP_%20gbXML_LTR_v03.pdf [accessed 15.02.15].

[56] Spanos I, Simons M, Holmes K. Cost savings by application of passive solar heating. Struct Surv 2005;23(2):111–30.

[57] Succar B. Building information modelling framework: a research and delivery foundation for industry stakeholders. Automat Constr 2009;18(3):357–75.

[58] Stundon D, Spillane J, Lim JPB, Tansey P, Tracey M. Building information modelling energy performance assessment on domestic dwellings: a comparative study. In: Raidén AB, Aboagye-Nimo E, editors. Proceedings for 31stAnnual ARCOM Conference. ARCOM; 2015. p. 671–9.

[59] Tiberiu C, Virgone J, Blanco E. Development and validation of regression models to predict monthly heating demand for residential buildings. Energy Build 2008;40:1825–32.

[60] Tucker P, Newton W. Carbon emissions from domestic built-in appliances, environment design guide, DES 74. 2009.

[61] US DE. Building energy software tool directory. 2015. http://apps1.eere.energy.gov/buildings/tools_directory/.

[62] Williams T. Modelling complex projects. London: Wiley; 2002.

[63] Wong KD, Fan Q. Building information modelling (BIM) for sustainable building design. Facilities 2013;31(3/4):138–57.

[64] Xu X, Yuan D, Sha H, Ji Y, Xu P. Energy consumption simulation of the prototypical building for optimizing the orientation of the building model in the simulated environment. In: The International Building Performance Simulation Association (ASim2012 Proceedings), November 25-27, 2012, Shanghai, China; 2012.